

AEROSOL DYNAMICS IN CONIFEROUS FORESTS

empirical and theoretical analyses



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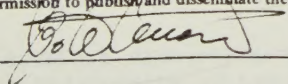


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Abstract Coniferous forests constitute an essential natural resource, exposed, however, to anthropogenically perturbed chemical and physical properties of the atmosphere. In particular, this thesis deals with coniferous forests as sinks for natural and anthropogenic aerosols. The problem is first approached by means of wind tunnel studies; the results indicate that anthropogenic aerosol dry deposition to forests is a significant part of the overall deposition from the atmosphere but also suggest that refined analyses through modelling and field experiments are necessary for a deeper understanding of mechanisms and quantities involved. This leads to a formulation of a partial differential equation model in aerosol concentration incorporating submodels of stand aerodynamics (such as wind speed and eddy diffusivity profiles), stand structure (such as vertical distribution of foliage) and aerosol mechanics. A first general model evaluation is carried out after reduction to a stationary version in horizontal (upwind of a forest wall and farther into the forest) and vertical (from canopy top and downwards) coordinates. Experimentally, a mature forest in southern Sweden (around the southern border of the boreo-nemoral region) is investigated with respect to aerosol concentrations, general contributions of sources and horizontal and vertical concentration gradients. A test of model predictions for this site relative to experimental data is carried out, indicating a satisfactory model behaviour. Significant increases of deposition rates around the forest edge are predicted. A non-stationary version of the model is then formulated and tested against field data for sub-canopy sulphur aerosol concentration variations with respect to a young spruce stand. In this application, above-canopy aerodynamics are also incorporated and submodels for particle transfer and stand structure are further detailed. Diurnal distinctions in deposition rates are predicted. The overall result from these studies is that aerosol dry deposition to coniferous forests has a pattern in space and time distinctly differing from large scale and long-term regional averages and implying, potentially, ecological effects of interest. Although several model evaluation phases remain, the model seems to hold a good potential for operational use.			
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empirical and theoretical analyses

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Master of Science in Electrical Engineering
Ld

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TO BRITA & BJÖRN, INGELA & SOFIA

*...an equation does not remove from the flow of
fluids its charm or mystery or its surprise.*

R.P. Feynman

*I have tried too in my time to be a philosopher,
but I don't know,
cheerfulness
was always
breaking
in.*

O. Edwards

Aerosol dynamics in coniferous forests

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empirical and theoretical analyses

Bo L B Wiman

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Summary

Acknowledgements

I Aerosol collection by Scots pine seedlings: design and application of a wind tunnel method. Oikos 36, 83-92 (1981).

II Aerosol depletion and deposition in forests - a model analysis. (In collaboration with G. I. Agren.) Atmospheric Environment 19, 335-347 (1985).

III Aerosol characteristics in a mature coniferous forest - methodology, composition, sources and spatial concentration variations. (In collaboration with H. O. Lannefors.) Atmospheric Environment 19, 349-362 (1985).

IV Aerosol concentration profiles within a mature coniferous forest - model versus field results. (In collaboration with G. I. Agren and H. O. Lannefors.) Atmospheric Environment 19, 363-367 (1985).

V A non-stationary model for sulphur aerosol depletion and deposition in a young spruce stand. Accepted for publication in Tellus (1985).



SUMMARY

Introduction

Why care about aerosols?

Three decades ago the capacity of coniferous forests to collect airborne particles grew increasingly evident, (Eriksson 1960). The recognition of this biogeochemical link added new aspects of the relationships between vegetation and the atmosphere. Thus a fascinating branch of plant ecology began to develop into the interdisciplinary field of forestry and atmospheric sciences and the study of man-made perturbations on biogeochemical cycles. Implied in these early findings was the idea that the structural and aerodynamic complexity of forest biomes must somehow have a bearing upon the efficiency of surface air scavenging. In other words, aerosol dry deposition seemed to be a process to a large extent governed by the forest landscape itself.

In those days, the atmospheric aerosol was mainly studied from the aspect of natural sources (marine bubble bursting, volcanic activity, aeolian soils), the increasing anthropogenic impacts on the physics and chemistry of aerosols by no means, however, escaping notice (Junge 1963). The already huge bulk of knowledge of plant-atmosphere relationships grew dramatically when research focused on the potential for severe inadvertent effects. The advancement of knowledge in the associated branches has been much promoted by the birth of efficient and fast multielemental analytical techniques for aerosol studies, notably the development of particle-induced x-ray emission analysis (PIXE) (Johansson *et. al.* 1970); by unifying approaches to the analysis and biophysical modelling of crop micrometeorology (e.g. Monteith 1975) and by the recognition of effects on forest productivity from acid and metal deposition (e.g. Ulrich and Pankrath 1983). Somewhere in the future there will be scientists attempting to write the history of the integrated science of "atmospheric plant ecology". One can only hope that such a work shall be able to conclude that knowledge advanced faster than the deterioration of the system it is dealing with.

What aerosols care about

In spite of the rapidly growing knowledge about aerosols a practice has continued of using large-scale regional and long-term averaged concepts when studying deposition problems. It seems that the full implications of landscape and forest structure for the spatial and temporal details of deposition patterns were given less attention as the study of plant-atmosphere interactions focused on the wet deposition problem. However, rain just falls - but aerosols care.

Airborne particles care - in a rather complicated way - about the structure and dimensions of a collector, e.g. a needle or a leaf. The collection efficiency, also involving parameters such as the velocity and size of the particle, can be studied experimentally and the results can, at least, show whether aerosols care enough about needles to justify further interest. This problem is approached in paper I.

Aerosols care about the manner in which air flow changes when approaching a forest wall. Such changes are related to the density and other structural characteristics of the forest and also depend upon the manner in which air above the canopy mixes with the inside air. One way to try to understand what will happen is through constructing a mathematical model. However, any

model attempting to capture even a slight fraction of what is assumed essential in the real-world system, soon grows complex and one is forced to use the efficiency offered by a computer. Paper II introduces such a model. Another way to get some insight into the forest-wall problem is, of course, to try to measure what are believed to be important clues in the field. Paper III deals with such measurements in a complex forest landscape.

However, aerosols are likely to care differently about things in theory and in practice. Therefore, of course, a mathematical model must be confronted with "reality" (or what is remaining of reality when disturbed by various measuring devices) for evaluation of the usefulness of the model. Paper IV compares model predictions for aerosol concentration depletion in a forest with measured data. The comparison is carried out for a certain type of situation assumed not to change with time (steady-state).

Aerosols may even care about whether it is day or night. This is because the air above and the air within a forest behave and mix differently during a 24-hour cycle. Further, the windspeed inside and above the canopy will normally increase when the sun is up. The larger the wind speed, the greater is the potential for aerosol capture by needles. On the other hand, the larger the number of needles, the larger is the damping of the wind velocity. Again, the net result of these and other counteracting mechanisms as reflected in the diurnal habits of aerosols can be investigated in the field. Such empirical information can, in turn, be used to test the quality of a mathematical model of what is believed to happen. Such a model evaluation - this time approaching the problems involved when conditions change with time (non-stationary) - is the scope of the final paper, no. V.

From these papers, it turns out that the spatial and temporal patterns of aerosol dry deposition are indeed to an essential degree governed by the structure and aerodynamics of forested landscapes. It can also be concluded, that the mathematical model seems to have a good potential for maturing into an operational tool.

However, whether forests and aerosols will ever care about the model is a mere consummation, devoutly to be wished.

The thesis

The aims of this work were:

- (1) to develop and apply laboratory and field methods for the analysis of aerosol depletion and deposition in coniferous forests;
- (2) to integrate relevant parts of forest micrometeorology, aerosol physics and aerosol chemistry into a framework for theoretical analysis;
- (3) to further develop this framework into a mathematical model describing steady-state as well as non-stationary situations with respect to aerosol depletion and deposition in forests;
- (4) to evaluate the quality of the model against field results.

Paper I

In the introductory phase of this work, little information was available regarding the collection efficiencies involved for aerosol dry deposition to coniferous forests. In order to estimate the order of magnitude of the deposition velocity for common field situations a wind tunnel was designed

and experiments carried out where pine seedlings were exposed to an artificial aerosol. Through cascade-impactor sampling and particle-induced x-ray emission analysis (PIXE) the aerosol particle size distribution was characterized as reasonably similar to those typical of anthropogenic atmospheric aerosols. For the wind speed 2.5 ms^{-1} , i.e. a value fairly representative of field conditions, a deposition velocity (per unit needle area) around 0.07 cm s^{-1} was obtained. Simplified calculations suggested that this should imply that the ratio of anthropogenic aerosol dry deposition rates relative to wet deposition rates to coniferous forests is of the order of magnitude of 10-20%. This paper also introduces a tentative basis for further field and modelling work.

Paper II

Although several approaches to the modelling of aerosol deposition onto natural surfaces have been suggested in the literature, few (if any) seem to have been designed to describe the effects of aerodynamic roughness transitions. Also, most models essentially use the concept of forests as aerosol sink surfaces. Paper II introduces a system of partial differential equations (pde) from the concept of forests as volume sinks and analyses the effects on aerosol depletion and deposition caused by forest walls from a steady-state version of the model. The model incorporates submodels of forest structure (leaf area index, vertical distribution of foliage), forest aerodynamics (wind speed, eddy diffusivity) and aerosol characteristics (collection efficiency, particle size distribution) and analyses the interplay between these submodels. The resulting pde is solved numerically for various forms of the submodels and results are presented graphically. Basically, horizontal (along a transect from an upwind open field into a forest) and vertical (along a transect downwards from the forest canopy top) depletion of particle concentration are found, notably for supermicron particles. The associated horizontal deposition patterns show distinct maxima around the forest wall. Vertical deposition patterns show maxima around height levels 50-80% of the stand height. Horizontal concentration depletion in dense forests is shown to follow an unexpected pattern where the concentration reaches a minimum a couple of stand heights downwind of the forest wall, then increases again farther downwind.

Paper III

A coniferous forest site within the boreo-nemoral region of Sweden is characterized with respect to basic structural properties and aerosol chemistry. Methods are developed for aerosol sampling in two size fractions along a horizontal transect (4 stations) from a peat bog and into a forest stand, and along a vertical transect well within the stand (4 stations) downwards through the canopy. Results include multielemental information (14 elements) on aerosol concentrations analysed with the PIXE-method. Some nitrate concentration data were also obtained. Basic site meteorology was recorded. The data base (around 2700 concentration data) is processed through multivariate techniques such as to yield insight into broad elemental relationships and sources. A soil-type group (K, Ca, Ti, Mn, Fe) and an anthropogenic group (S, V, Cr, Ni, Pb; essentially long-distance transports) are suggested. Time averaging procedures show that there are spatial concentration variations along the transects, notably for supermicron particles. The general trend for coarse aerosol fractions is a concentration decline inside the forest near the forest wall followed by an increase farther in. Concentration variations of fine aerosol fractions show no distinct trends. The results are qualitatively consistent with the existence of particle losses due to deposition and inputs due to turbulence and gravitationally settling particles.

Paper IV

Representative field concentration data (S and Ti) from paper III are compared with predictions by the model developed in paper II. For this evaluation of model performance, available site-specific structural and particle size information are used for the submodels. Steady-state conditions are assumed. Though field data are not sufficient for a complete model evaluation, the tests do not indicate any fundamental model deficiencies.

Paper V

The earlier papers have mainly focused on the steady-state dynamics of the forest-aerosol system. The system is, however, changing with time on several time scales of interest. This paper introduces a non-stationary version of the basic model developed in paper II. The structure of a young spruce stand (leaf area index, vertical foliage distribution, needle diameters) was analysed. Stand micrometeorology was recorded during 120 hours in summer. Structural and micrometeorological data are processed to submodel formulations of structure and aerodynamics and entered into the pde-model. Aerosol sulphur concentrations above and within the stand were measured in two particle size fractions (time resolution 12 hours) as were number concentrations in 7 size classes by means of an optical particle counter. A limited cascade-impactor sampling was also employed. These methods of aerosol characterization are used for reasonable formulations of the upper (above-canopy) boundary conditions for the model. Model predictions for sulphur aerosol concentrations within the canopy are compared with empirical data and found acceptable, although not supportive of full operational capacity of the model. The complete solution of the model with respect to time and height above ground is shown graphically for concentration and deposition. A distinct diurnal deposition pattern is demonstrated, with deposition rates increasing during day.

Conclusions

The work has shown, with an interdisciplinary approach, that aerosol dry deposition to coniferous forests has a pattern in space and time distinctly differing from large scale and long-term regional averages and implying, potentially, ecological effects of interest. The mathematical model, although not yet fully applicable on a real-world forest landscape, seems to hold some potential for operational use.

An essential question then is: having shown that the model is capable of a meaningful handling of a complex problem - how proceed towards operationality? The path to explore should be: refinement - evaluation - corroboration - and, if possible, simplification - generalization - application. There are, of course, theoretical as well as empirical phases in this chain of systematic sensitivity and key-factor analyses. The critical factors are (1) submodels of particle size distributions, (2) leaf surface area distributions, (3) deposition velocity functions and (4) particle transfer functions.

The factors (1) and (2) essentially relate to whether access to accurate and rapid empirical methods can be counted on along the path towards operationality; I judge this is the case. Factors (3) and (4) also involve complex theoretical issues to be solved. For instance, several details of the micro-scale flow regime within the array of needles (or leaves) in forests are not well known. The deposition velocity submodel used in the present study catches some characteristics of this milieu,

but has to be further broken down to incorporate e.g. the Reynolds number, interception, blow-off and several other mechanisms; further, a non-linear composition of various collection mechanisms may be considered. However, a unifying theory covering particle sizes ranging four or more orders of magnitude and shapes from hollow aggregates to ideal spheres will not develop easily, if at all. For years to come, these issues must be approached with 'simplifying assumptions in order to obtain an idea, albeit rough, of the phenomenon being examined', (Fuchs 1964). Particle transfer is described, in the present study, with a mass-momentum similarity approach. There may be reasons to consider whether there are situations where particles do not care much about the Reynolds analogy.

Finally, an operative model must be able to handle landscape topography, other types of sinks (such as deciduous forests, lakes) and also the complications of winter and snow-covered vegetation. Remembering that no model can be corroborated without access to empirical information, the path to full operationality is no easy one. On the other hand, it does seem to exist.

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*

Göran Agren	always understanding the wildest ideas; skilfully processing them through mathematical purgatories where a few survived
Hans Lannefors	aerosol hunter, particle inducer, cray-fish-catcher; emitting on the correct wavelength
Bengt Nihlgård	giving me a strange paper (1972) on something called aerosols; always available ever since
Gunn Hansson	conscientious laboratory assistant and wind tunnel runner
Germund Tyler	constructively providing one of the motives
Håkan Staaf	skilled decomposer and cultivator; tie-breaker with (at times) a tricky serve
Folke Andersson	systems ecologist; breaker of barriers
Nils Malmer	Head of the Department, letting an electro-technician in among the plants
Hans-Christen Hansson	the infinite-wall particle trapper, heating any discussion
Gert Cöster	<u>knows</u> about his forests; permitting me access to them; always prepared with the gentle giant
PIXE-people, a dozen or so	letting an ecologist in among the particles; performing pure magic with sampleshifting devices
ESP-people, a score or so	environmental studies programmers, providing that extra sensory perception

Colleagues at the Department of Plant Ecology
 Friends in the Boalt Study area
 Friends at IVL, SMHI and MISU
 Unknown, constructively critical actors

Nearest and dearest - the most vital ingredients of this project

*

All have contributed to the merits of this work - none to its shortcomings.

*

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